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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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Abstract

SNAP-8 development has included extensive startup testing of the power conversion system coupled with a reactor simulator. Data are presented that show the power conversion system can be started in a dependable way. The temperature transients are well within the limits specified for the reactor. Procedures are discussed for the relatively fast transient to self-sustained operation and for the more gradual transient that achieves rated power output.

Introduction

SNAP-8 is a reactor-powered electrical generating system being developed for use in space. The system has a turboelectric power conversion system operating on the mercury-Rankine cycle. Considerable attention has been directed towards defining startup procedures for the power conversion system. The procedures must be dependable and, at the same time, compatible with the operational constraints of the reactor.

Startup studies have been both analytical and experimental. Computer simulations were used to formulate promising startup procedures and to point out problem areas requiring experimental investigation (Refs. 1, 2). The experimental startup work began in 1965 when a simplified mercury-Rankine system was coupled with a reactor simulator at Lewis Research Center. This system was used to study reactor loop transients during startup of the mercury loop (Ref. 3). In 1968, the contractor for the power conversion system (Aerojet-General Corporation) conducted a series of startup tests on a power conversion system using a gas-fired heat source. In these tests, the feasibility of completely automatic startups was demonstrated. The culmination of the startup work came in 1969 at Lewis Research Center when 135 startup tests were conducted on a power conversion system coupled with a reactor simulator. For the first time, startup procedures for a complete power conversion system were experimentally evaluated concurrently with realistic reactor loop transients. The results are discussed in this paper.

Test System and Startup Method

System Description

The test system in the startup program was essentially a complete power conversion system coupled with a reactor simulator and radiator simulator. These simulators were used so that the tests would include the dynamic interactions of these components with the power conversion system. The test system was assembled in breadboard fashion rather than flight configuration; however, attention was given to preserving the first-order dynamic characteristics of a flight-configured system.

A simplified diagram of the test system is shown in Fig. 1. The reactor simulator used an electric heater configured similar to the reactor. A power controller matched the heater electrical power with the time-varying reactor power signal from an analog computer. Details of the reactor simulator are given in Ref. 4. Heat from the reactor simulator was carried by 1300° F NaK to the mercury boiler. Mercury vapor from the boiler drove the turbine-alternator. Turbine exhaust flowed into the condenser where it was condensed, subcooled and returned to the mercury pump. The condenser was cooled by NaK and the waste heat was rejected by the radiator simulator. The air-cooled heat exchangers of the radiator simulator had a heat capacity equal to the anticipated heat capacity of the space radiator. This heat capacity, together with feedback control on the outlet temperature, allowed simulation of the steady-state and transient characteristics of the radiator (Ref. 5). All loops used prototype centrifugal pumps driven by electric motors. The power for the pump motors was supplied by the turbine-alternator.

In order to provide flexibility in conducting the test program, the controls and other equipment necessary for startup were not flight-type. A gas-pressurized reservoir (Fig. 1) was used to injet the mercury-loop inventory during startup. An electrohydraulic flow control valve in the mercury loop was used in a feedback control of mercury flow. A pneumatic flow control valve in the heat-rejection loop was used in feedback control of the condenser coolant flow. This flow control was part of the condenser pressure control system to be discussed later. The other valves shown in Fig. 1 were used in the on-off mode. Valve sequencing and other procedures were automated in 27 startups by use of a start programmer (ref. 6). Additional details of the test system are provided in Ref. 7.

Startup Method

In SNAP-8 startup, the first step is to start the reactor and slowly bring the reactor and boiler to operating temperature with the mercury loop evacuated. During this time the pumps in the NaK loops are running at reduced speed on battery-supplied inverter power. When the temperatures have stabilized, the startup of the power conversion system begins.

First, the mercury pump is started with the inverter. Then the mercury reservoir valve (Fig. 1) is opened and mercury fills the liquid lines from the condenser outlet valve to the boiler inlet valve. Next, the boiler inlet valve is opened and the flow control valve starts the flow ramp to the "self-sustaining" mercury flow, drawing inventory from the reservoir. Self-sustaining mercury flow is defined as the steady-state flow that provides a safe margin of turbine-alternator power over that required by all the pumps at rated speed. When the output frequency of the accelerating turbine-alternator matches the frequency of the auxiliary power going to the pumps, the pumps are transferred to alternator power. The turbine-alternator-pump combination then "bootstraps" itself to rated speed. That is, the mercury pump provides the flow of power to the turbine, and the turbine-alternator in turn, provides the power for the pump. At the end of the mercury flow ramp, the valve at the condenser outlet is opened. The mercury reservoir valve is closed when the desired amount of inventory has been injected into the system. The mercury loop is then a closed system with the pump inlet pressurized by the condenser. Pressure at the inlet of the condenser is controlled by the flow control in the heat-rejection loop.

The startup sequence provides for a time-delay between the conclusion of the bootstrap operation and the start of the second ramp in mercury flow. This delay allows reactor loop transients to subside. The second ramp starts at the self-sustaining mercury flow and concludes at the flow that gives rated power output. This ramp, therefore, is called the power ramp. At the end of the power ramp, the SNAP-8 system is ready for use. The complete startup transients of mercury flow, speed of the rotating components, and net power output of the alternator are shown in Fig. 2.

Results and Discussion

Bootstrap Operation

The most critical part of the startup is the bootstrap operation. A large share of the startup runs, therefore, were devoted to studying this operation. Ninety-one runs were made where some, or all, of the pumps were brought to rated speed by the accelerating turbine-alternator. One of the prime variables in these runs was the rate at which the mercury flow was ramped up to the self-sustaining flow. The objective was to determine the ramps that would give dependable bootstrapping and, at the same time, cause minimum disturbances in the reactor loop.

Maximum limit for duration of mercury flow ramp. - A startup showing the maximum limit for duration of the bootstrap ramp is shown in Fig. 3. Mercury flow and turbine-alternator speed are shown as functions of time. The mercury flow was started up on a

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ramp with an intended duration of 145 seconds, indicated by the dashed lines. After the pumps were transferred to alternator power at 70 seconds, the turbine-alternator and pumps accelerated slowly towards rated speed. The acceleration was so slow that the mercury flow dropped off the desired ramp. As the turbine-alternator approached rated speed, a small increment of load due to the activation of the speed control was added to the alternator load at approximately 100 seconds. With this addition, the load exceeded the available power, causing the turbine-alternator to decelerate rapidly. The mercury flow came down, too, due to the deceleration of the pump. At this point, the pumps were manually transferred to an auxiliary power supply, allowing the turbine-alternator to recover its acceleration to rated speed. Otherwise, the startup would have been unsuccessful.

An understanding of the problem experienced in this run can be gained from Fig. 4. This is a sketch of the speed and power characteristics of the turbine and pumps during a typical bootstrap operation. In the speed plot, the initial pump speeds are represented by the horizontal dashed line. The intersection of this dashed line with the turbine speed curve represents the time of the pump transfer from auxiliary power to alternator power. The remainder of the speed curve, up to rated speed, applies to both the pumps and turbine and represents the bootstrapping. The turbine power provided by the mercury flow ramp and the pump power load on the turbine-alternator are shown in the power plot. The shaded area represents the power margin between the turbine and pumps. The turbine will accelerate at a rate proportional to this margin. The minimum power margin occurs when the turbine approaches rated speed because the power requirement of the pumps goes up approximately with the cube of the speed. If the duration of the mercury flow ramp is too long, the pumps will be requiring close to their rated power before the turbine power has reached the self-sustaining level. With a small power margin any perturbation, such as the one experienced in the run shown in Fig. 3, could cause deceleration of the turbine.

Startup test data in Fig. 5 show the minimum turbine power margin as a function of mercury flow ramp duration. As shown in the figure, the turbine power margin for the shorter ramps was equal to the steady-state value associated with the final flow of the bootstrap ramp. However, as the ramp duration increased, the minimum power margin during the ramp decreased until it was essentially zero for a ramp of 145 seconds duration.

Minimum limit for duration of mercury flow ramp. - Decreasing the duration of the mercury flow ramp from the 145-second limit, therefore, increases the turbine power margin for bootstrapping. In doing this, however, consideration must be given to two factors that tend to impose a minimum limit on the ramp duration. The first of these was a problem encountered in the mercury loop involving the transient pressure-drop characteristics of the boiler. The second was the concern regarding reactor loop transients.

Figure 6 illustrates the mercury loop problem. Parameters shown are pump and turbine speeds, pump discharge pressure, boiler inlet and exit pressures, and mercury flow. The mercury flow ramp was intended to be linear with a duration of about 30 seconds (dashed lines). While the mercury pump was still at its initial speed, however, the flow fell off considerably from the intended ramp. This was due to the nature of the pressure transients. Comparison of the boiler exit pressure transient with the mercury flow ramp indicates that boiling began abruptly at approximately 28 seconds. Then, the boiler inlet pressure rose sharply to a level approaching the mercury pump discharge pressure. Consequently, the reduced pressure drop available for the flow control valve, meant the scheduled flow ramp could not be maintained. A higher initial speed of the mercury pump, of course, would overcome this problem.

The initial speed of the mercury pump required to maintain the flow ramp was related to the duration of the mercury flow ramp. Figure 7 shows this relation. For a given ramp duration, initial pump speeds above the curve produced sufficient pump discharge pressure to maintain the intended mercury flow ramp, despite the surge in boiler inlet pressure; initial pump speeds below the curve did not. As shown in the figure, the mercury pump initial speed requirement increased by approximately a factor of 2 in going from a 145-second ramp to a 30-second ramp. The battery power required to drive the pump at the higher speed would increase by a factor of 8. For the mercury pump alone, the power involved would be small, and the factor of 8 would not be significant. For simplicity, however, all pumps of the system should have a common auxiliary power supply and run at the same initial speed. For this reason, the factor of 8 becomes important.

As already mentioned, the transient imposed on the reactor is the second factor that tends to dictate a minimum limit for the duration of the mercury flow ramp. When the mercury flow is ramped to the self-sustaining level in a short time, heat is extracted suddenly from the boiler and, therefore, the temperature of the NaK entering the reactor may drop too quickly. Consequently, the rate of change of reactor inlet temperature is an important startup constraint. An excessive temperature change in a short time interval could cause undesireable thermal stressing of the fuel elements. The effect of ramp duration on maximum temperature change in 10 seconds at the reactor simulator inlet is shown in Fig. 8. There was a definite increase of the temperature change as ramp duration was decreased. The startups using a 30-second ramp had an average 10-second temperature change that was about twice as large as the change for the 140-second ramp. Still, the average temperature change for the 30-second ramp was well below the reactor constraint shown by the dashed line. The increase in the temperature change became steeper when the durations became less than about 90 seconds. For ramp durations of about 90 seconds the value of the temperature change in 10 seconds was a factor of 3 from the reactor constraint. A more detailed discussion of the reactor loop transients obtained in the test program is presented in Ref. 8.

Selection of ramp. - In selecting the mercury flow ramp duration for the bootstrap operation, consideration must be given to the maximum limit associated with the turbine power margin and the consequences of backing off too far from this limit. It has been shown that a penalty is paid in battery power required for the pumps as the ramp time is decreased. Another consequence of the shorter ramps is the increase in the reactor temperature rate of change. For convenience, the trade-offs involved in selecting the ramp duration are shown together in Fig. 9. From Fig. 9, it can be seen that ramp durations in the range of 80 to 100 seconds provide almost the steady-state value of turbine power margin and require relatively low battery power for the pumps. With ramps in this range, the maximum temperature change at the reactor simulator inlet in a 10-second interval provides a safety factor of 3 from the constraining value for the reactor.

Condenser pressure control. - Another important consideration in the bootstrapping of the system to the self-sustained condition is the buildup and stabilization of the condensing pressure. Associated with the self-sustaining level of mercury flow is an upper limit of condenser pressure, since this pressure is the turbine back pressure. During the mercury flow ramp, the pressure must not build up towards this limit too quickly, or the turbine acceleration will be impeded. A lower limit also exists, once the injection process ends, since then, in zero gravity, the pump suction pressure is essentially equal to the condenser pressure. Unless the suction pressure is some amount above the mercury vapor pressure, the pump will cavitate and fail to produce the self-sustaining flow. Because of these limits a condenser pressure control is used in the startup.

The control concept is shown in Fig. 10. The lower sketch shows the mercury flow ramp to the self-sustaining level. The upper sketch shows the allowable corridor for the condenser pressure as prescribed by the requirements in turbine back pressure and pump suction pressure. The cross-hatched areas represent the unacceptable values. The control is a deadband type. Corrective action is taken whenever the pressure goes outside the deadband indicated by the dashed lines in the allowable corridor. The corrective action is shown in the middle sketch and consists of ramping the condenser coolant flow upwards when the pressure is above the deadband and downwards when the pressure is below the deadband. The control is not allowed to operate during the initial buildup of the pressure into the deadband. Instead, an initial flow of coolant is used to govern the rate of this buildup.

During the test program, the capability of the control was investigated for various values of the control parameters and for variations in the startup procedures which subjected the control to extreme condenser transients. The testing showed that deadbands as small as

2 psi could be used without excessive oscillations of the pressure provided the ramp rate of the coolant flow was low. With this ramp rate low, however, initial overshoot of the deadband and, hence, high turbine back pressure was a problem for some startups. The overshoot problem was corrected by doubling the speed of the coolant flow ramp to a value of about 30 percent of rated NaK flow per minute. With this higher rate, deadbands of 3 or 4 psi were required for good stability. The zero-gravity requirement for pump suction pressure was satisfied by using initial coolant flows below about 15 percent of the rated value.

The performance of the control during extreme condenser transients is illustrated in Figs. 11 and 12. In the startup of Fig. 11 the mercury flow was ramped up to the self-sustaining level in 30 seconds rather than in the preferred time of 80 to 100 seconds. In the startup of Fig. 12 more than twice the design value of liquid mercury was allowed to accumulate in the condenser before injection was stopped. For both startups, the pressure response was satisfactory in regards to initial overshoot, oscillation, and pressure at the end of injection. Tests such as these showed that the control could cope with a wide range of conditions in the bootstrap operation.

Power Ramp

Stabilization time. - Early startup concepts for the SNAP-8 system called for the mercury flow ramp to the rated power level to begin very shortly (100 to 200 sec) after the ramp to the self-sustaining level. The basis of this concept was to take advantage of the initial, transient surge in reactor power. More recently, however, planning for potential missions has shown that the probable configuration of a flight-type system would include a stand-by power conversion system coupled to the same reactor. With such a configuration, the transient characteristics of the reactor's power surge would be dependent on which power conversion system was being started. Therefore the transient matching of the power ramp in mercury flow to the reactor's response is impractical. The current concept is to wait until the transients in the reactor loop have died out before beginning the power ramp.

An indication of the length of time required for this stabilization is illustrated in Fig. 13. The reactor loop transients are diminished after the first cycle of power or temperature. The system is almost steady after the second cycle. It is important to realize that the stabilization time needed for a flight system may be different than that indicated by the ground-based tests. The differences could be due to changes in the reactor loop heat capacity or to changes in the reactor temperature coefficients of reactivity. The coefficients used in the simulator were the coefficients determined in tests of the latest reactor, the SNAP-8 Development Reactor. Coefficients expected for a flight reactor would provide closer control of temperature and, thus, tend to allow shorter stabilization time.

Effect of ramp duration. - Once stabilization is achieved the system is ramped to full power operation. Figure 14 shows reactor simulator transients during a 500-second ramp to full power operation. It is apparent that the changes are occurring almost on a quasi-steady state basis. The curves are smooth between self-sustaining power operation and full-power operation. The minor irregularities in the power and outlet temperature traces are due to the simulated reactor control steps. The reactor could easily tolerate a ramp duration of 500 seconds or longer. With improved temperature coefficients of reactivity, even shorter power ramp durations would be compatible with the load-following capabilities of the reactor.

Problems in condenser pressure control, however, were encountered in the 500-second power ramp. As shown by the condenser pressure plot in Fig. 15, these problems began at about 360 seconds into the ramp. Up to this time, corrective actions of the control had forced the condenser pressure back into the deadband whenever it exceeded the upper limit. The stepwise increase in the coolant flow during this time indicates that the control was operating correctly. After 360 seconds, however, the pressure remained above the deadband even though the control ramped the coolant flow upwards in a continuous manner. This situation indicates the ramp rate of the control was too small for the 500-second power ramp even though it was set close to the optimum value for the bootstrap operation discussed previously. Another problem is evident near the end of the ramp. At about 450 seconds, the control lost its ability to increase the coolant flow; the maximum flow limit of the heat-rejection loop was reached. The pressure, therefore, increased further.

These two problems could be corrected to allow use of a 500-second power ramp. A variable ramp rate in coolant flow could be built into the condenser pressure control to allow it to cope with both the bootstrap operation and a fast power ramp. And the transient flow capacity of the heat rejection loop could be made greater than what is required for the steady-state rated power operation of the system. However, when the disadvantages of control complexity and increased pumping power are considered, the more attractive solution is to slow down the mercury-flow power ramp.

A 900-second power ramp is shown in Fig. 16. For this ramp in mercury flow, the control had the same coolant-flow ramp rate as in the previous figure. Of course, it also had the same maximum flow limitation. Both were sufficient for the 900-second power ramp. The condenser pressure was maintained within the deadband throughout the transient. Additional data and discussion related to the power ramp are included in Ref. 10.

Summary of Results

One hundred thirty-five startup tests were conducted on a SNAP-8 power conversion system coupled with a reactor simulator. Both the relatively fast transient to a self-sustained condition and the gradual transient that achieves rated power were investigated. The investigations have shown that satisfactory startup of the power conversion system can be ensured with procedures that will treat the reactor very gently.

The more specific results of the testing are as follows:

1. Startup to the self-sustained level was successfully accomplished with mercury flow ramps up to a maximum limit of 145 seconds in duration. The turbine power margin, however, for acceleration of the turbine-alternator and pumps to rated speed was larger for shorter ramps. Ramp durations of 80 to 100 seconds provided substantial margin and still caused minimal reactor loop transients. The short-term temperature change at the inlet of the reactor simulator was only about 1/3 of the specified acceptable value for the reactor.

2. A simple deadband control of condenser pressure effectively coped with a wide range of condenser conditions during the transient to self-sustained operation. The control is required to limit turbine back pressure and maintain adequate mercury pump suction pressure.

3. A 500-second mercury flow ramp from the self-sustaining level to the rated-power level was very compatible with reactor-simulator load-following capabilities. In fact, reactor simulator temperatures indicated the change in operating point was almost quasi-steady. The 500-second ramp, however, exceeded the capability of the condenser pressure control as optimized for the first phase of startup. Slowing the power ramp down to 900 seconds enabled the control to perform satisfactorily without complicating changes in the control.

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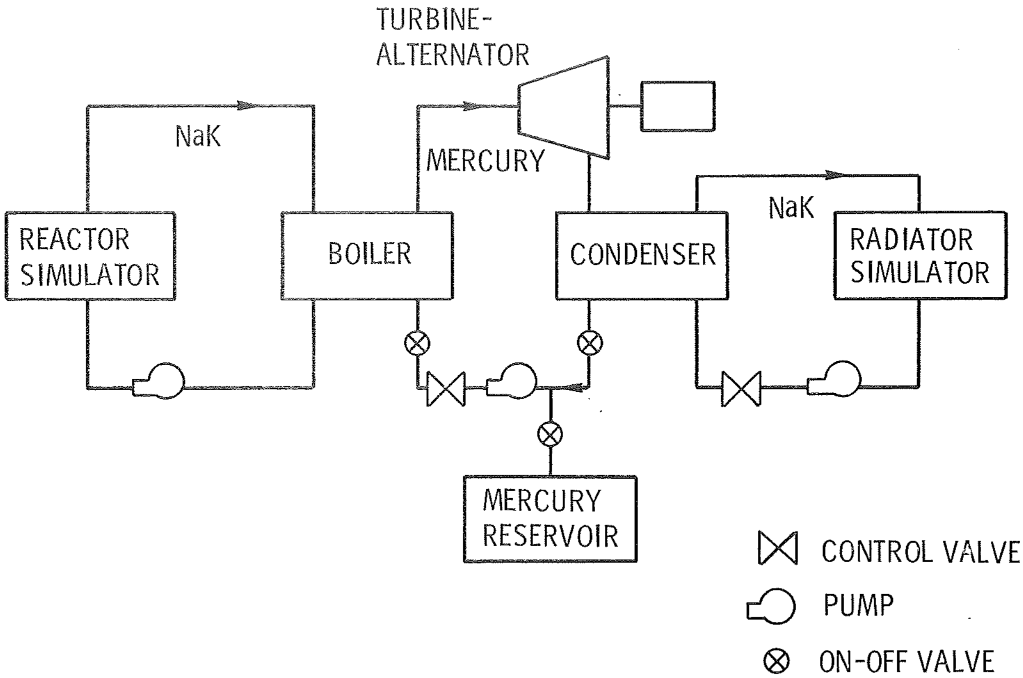

Figure 1. - SNAP-8 test system.

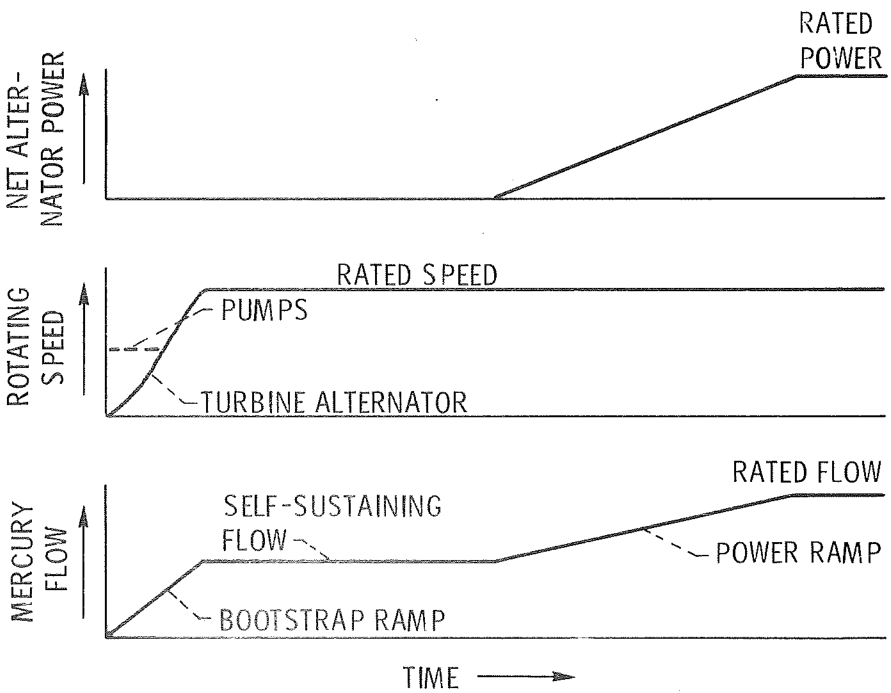

Figure 2. - Startup profiles of mercury flow, rotating speeds, and net alternator power.

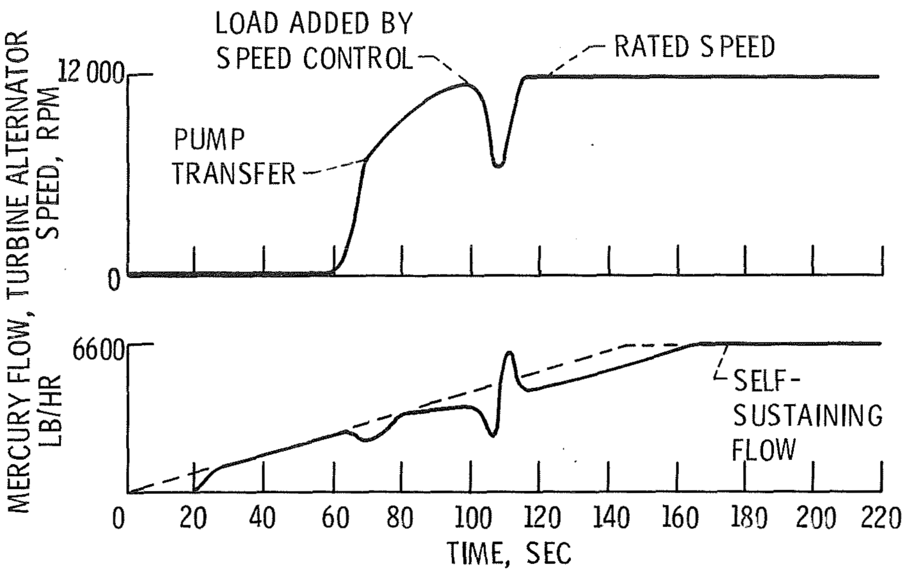

Figure 3. - Startup run illustrating maximum limit for duration of bootstrap ramp.

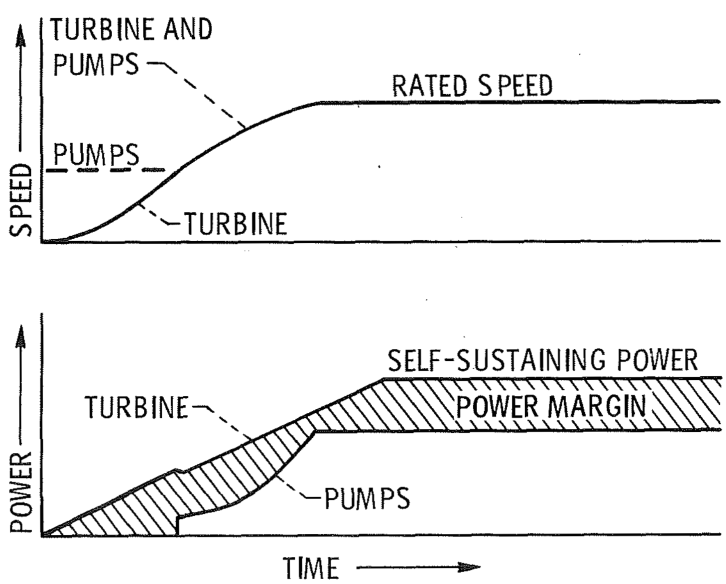

Figure 4. - Speed and power characteristics during the bootstrap ramp.

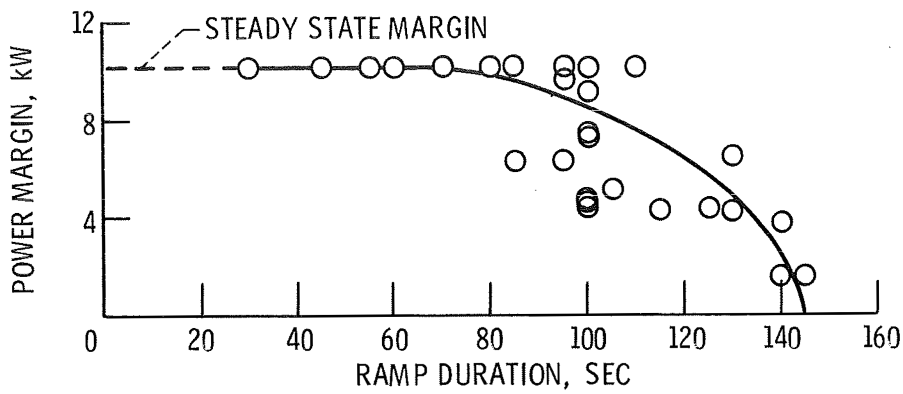

Figure 5. - Effect of mercury flow ramp duration on minimum turbine power margin.

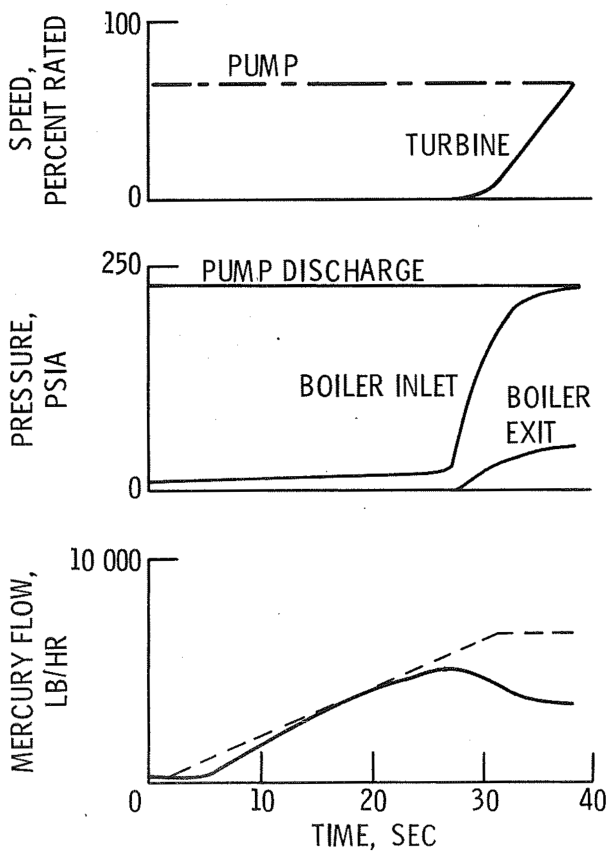

Figure 6. - Initial mercury loop characteristics for a 30 second mercury flow ramp.

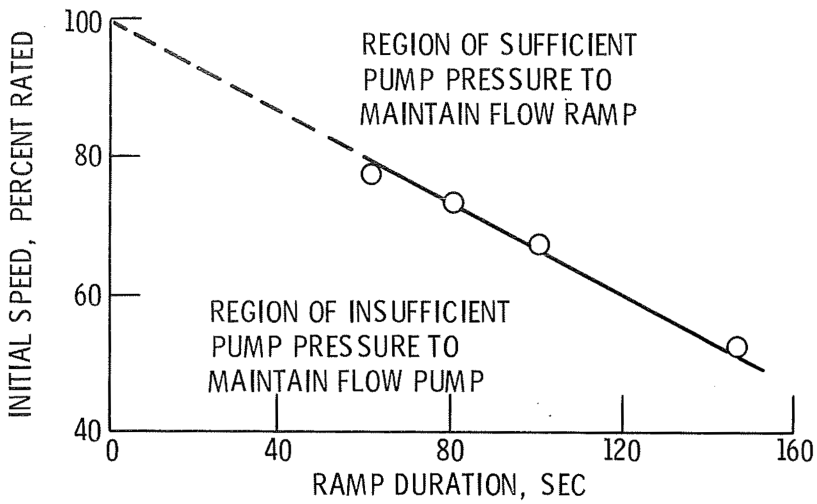

Figure 7. - Effect of mercury-flow ramp duration on minimum initial speed required for mercury pump.

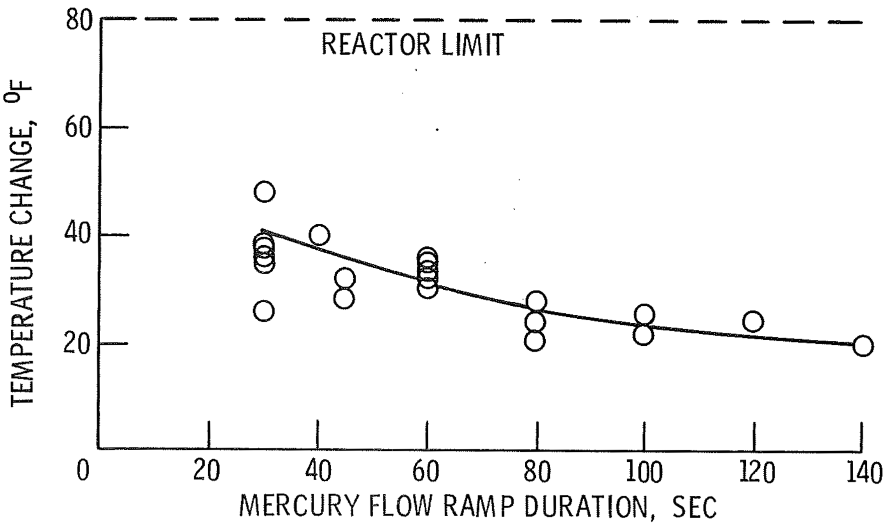

Figure 8. - Effect of ramp duration on maximum temperature change in 10 seconds at reactor simulator inlet.

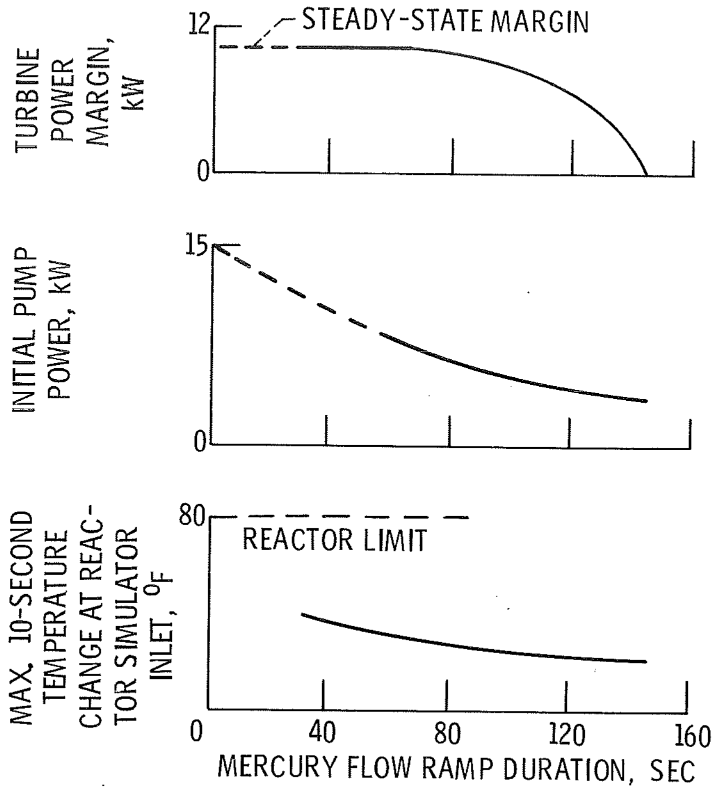

Figure 9. - Trade-offs involved in selection of mercury flow ramp for bootstrap operation.

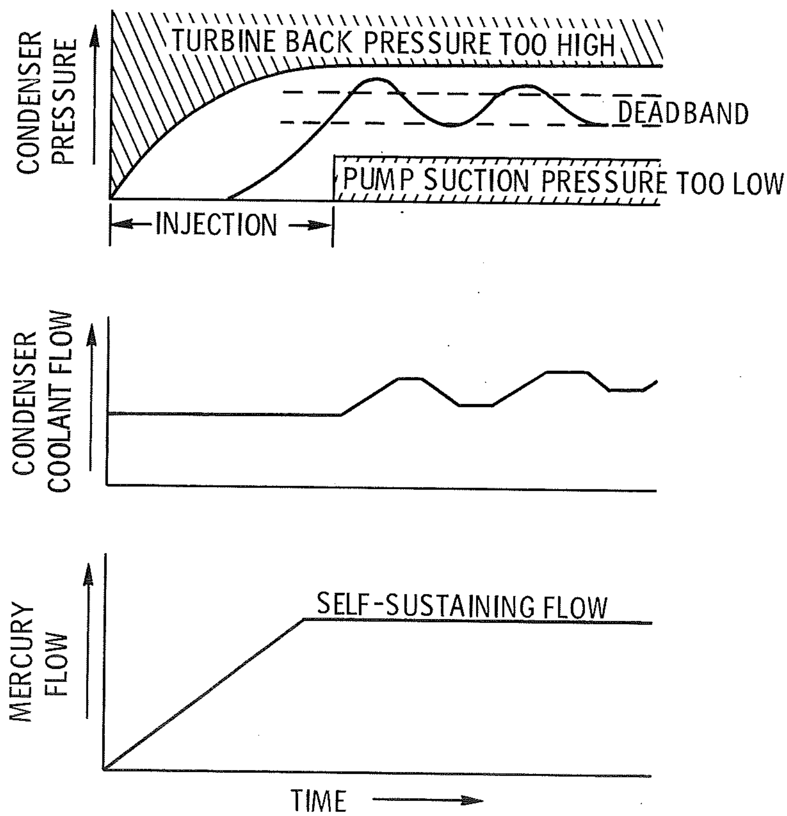

Figure 10. - Condenser pressure control concept.

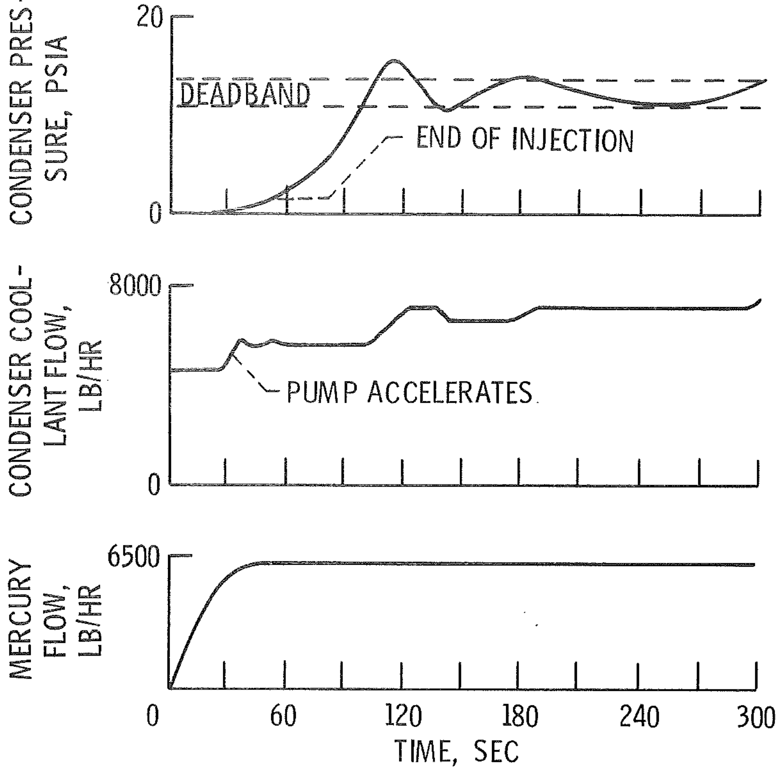

Figure 11. - Performance of condenser pressure control with 30 second mercury flow ramp.

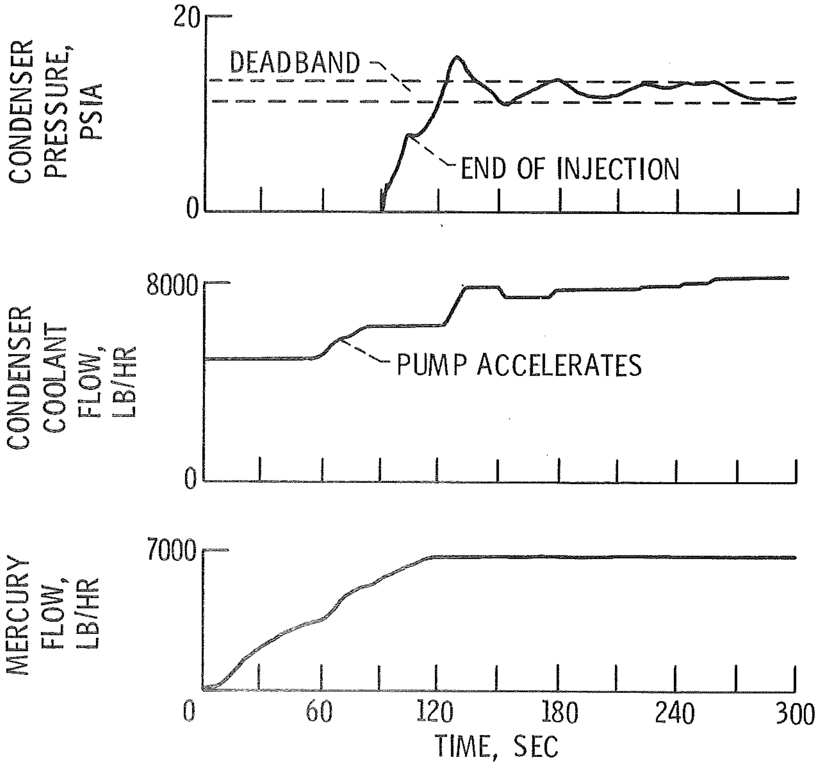

Figure 12. - Performance of condenser pressure control with 100 pound condenser inventory.

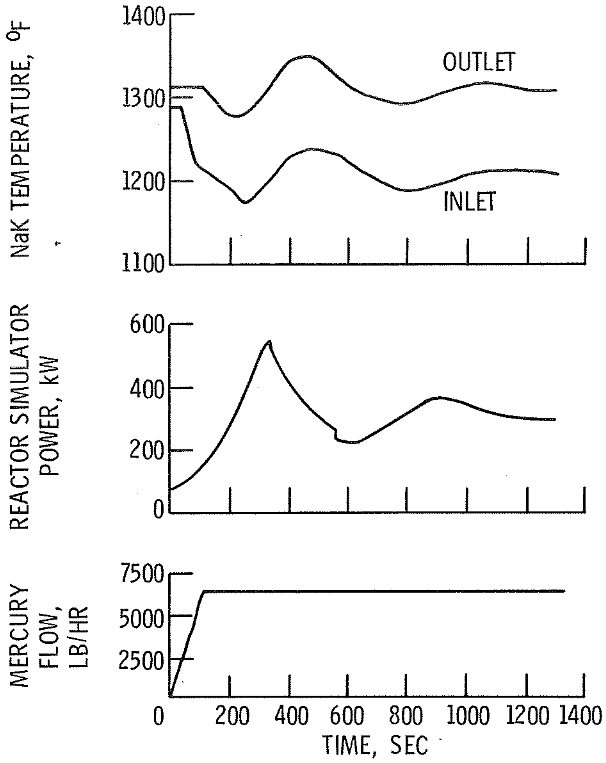

Figure 13. - Reactor loop transients dying out after bootstrap operation.

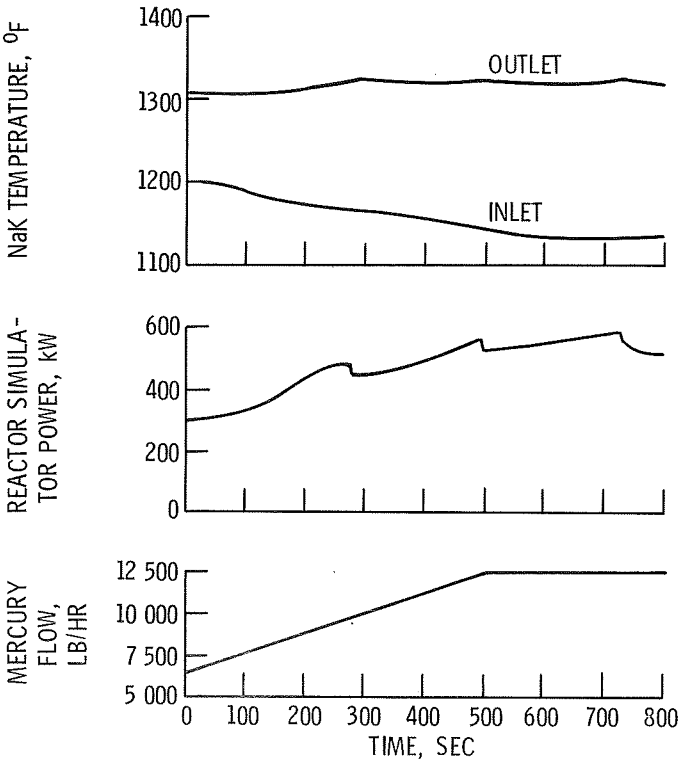

Figure 14. - Reactor loop transients for a 500 second power ramp.

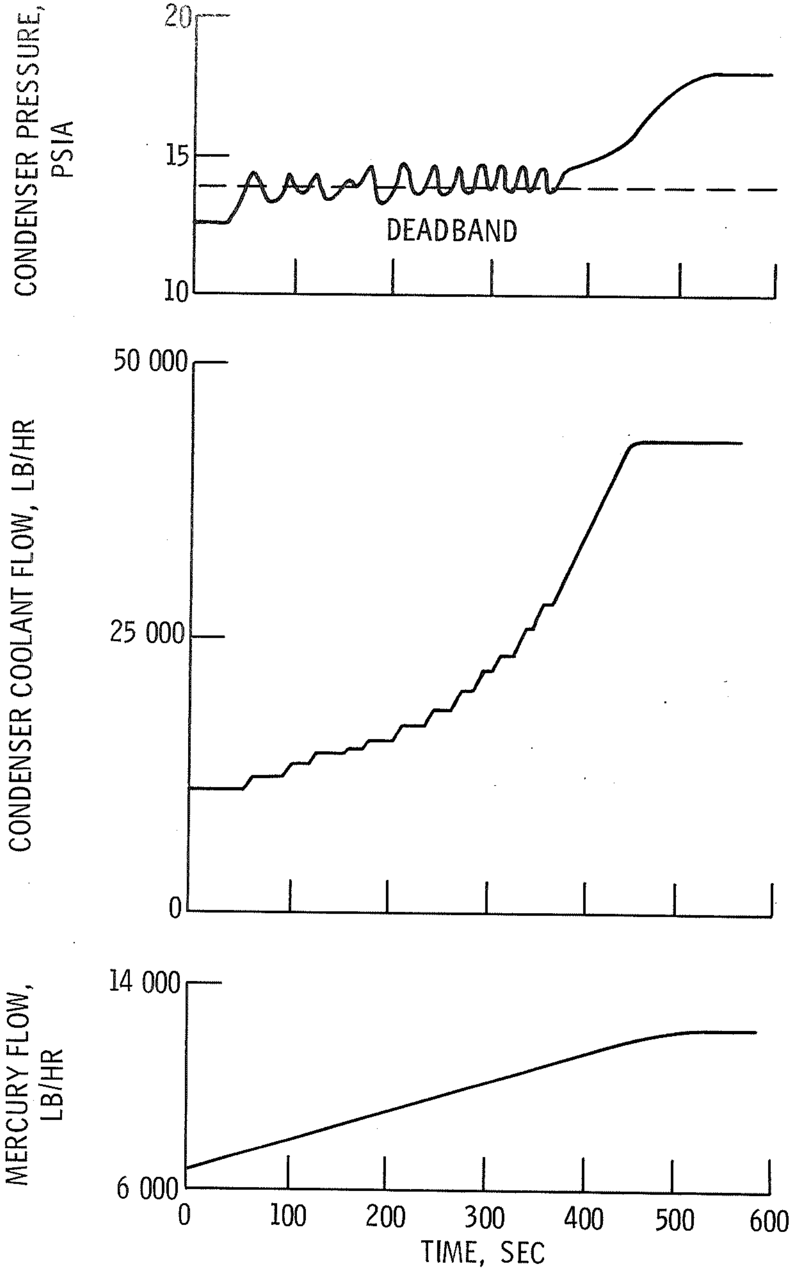

Figure 15. - Inadequate control of condenser pressure in 500 second power ramp.

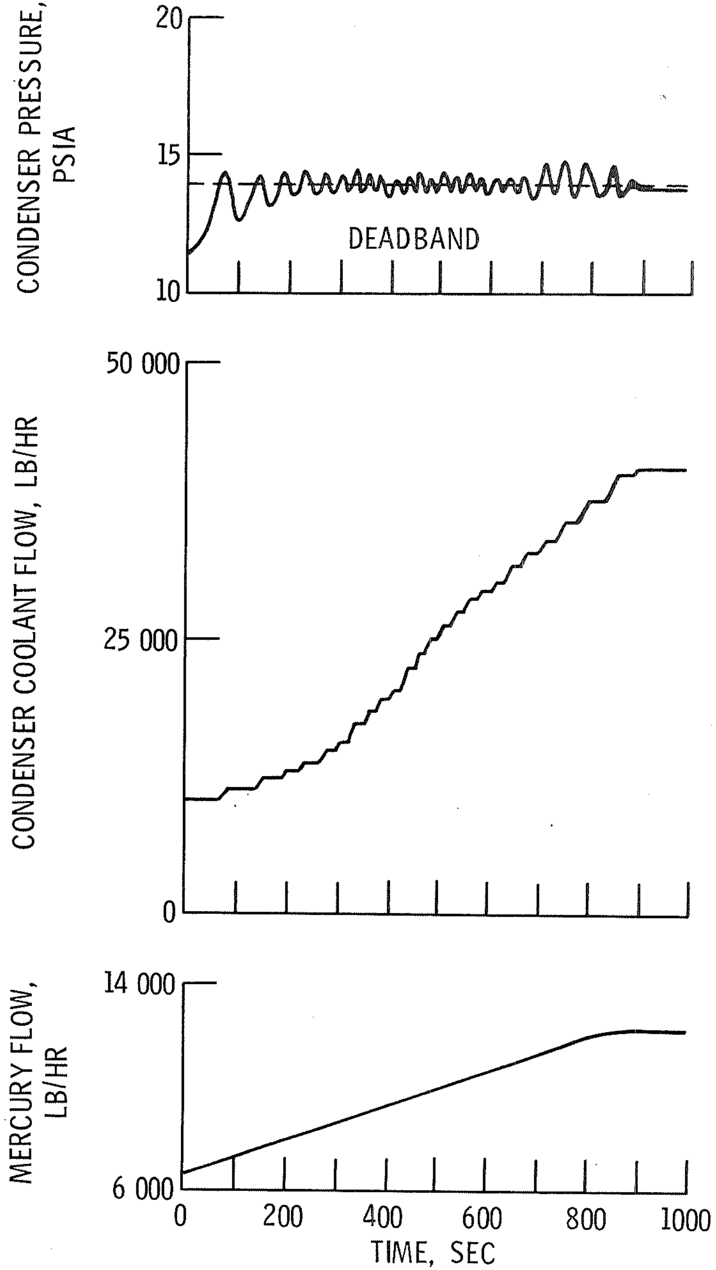

Figure 16. - Acceptable control of condenser pressure in 900 second power ramp.